# System Considerations for Actinide Recycle in Fast Reactors


***Chester S. Ehrman***
***Burns and Roe Company***
***Oradell, New Jersey, USA***

***Charles E. Boardman,***
***General Electric Company***
***San Jose, California, USA***


## Abstract


The benefits that can be achieved by completing the development of the Advanced Liquid Metal Reactor (ALMR) and the electrometallurgical recycle system (Actinide Recycle System) can far exceed the cost of the remaining development program. Use of the ALMR/Actinide Recycle System to close the back end of the fuel cycle provides for lower costs to the Government (taxpayers), the electric power industries, and the rate payers. These cost benefits and other advantages to the U.S. nuclear program are discussed.


## Introduction

Problems encountered with the U.S. Yucca Mountain repository program have resulted in the need to delay the date when spent fuel could be received for direct disposal from 1998 to 2010. Further delays and significant cost increases have been forecast by several organizations.

The U.S. Government now plans to meet its obligation to accept spent nuclear fuel from commercial LWRs in 1998 by providing multipurpose canisters for the shipment and storage of the spent fuel at a central interim storage facility. Site work and analysis of the deep, geologic repository at Yucca Mountain will continue at a reduced level of effort. This provides the time required to reevaluate the use of fuel recycling instead of direct disposal.

Most other nations with sizable commercial nuclear power programs are in the process of or are planning to recycle the spent fuel that is being discharged from their Light Water Reactors (LWRs) in order to conserve energy resources and to condition the waste for disposal. With this approach, the economic and environmental advantages of nuclear power will remain available through the 21st century and beyond and the environmental risks associated with direct disposal of spent fuel will be reduced by conditioning the waste prior to disposal. Over the past 10 years the U.S. Government has funded an ALMR design team lead by the General Electric Company (GE) and a fuel cycle development team lead by Argonne National Laboratory (ANL).[1] These teams have made substantial progress in developing a competitive ALMR and a fuel cycle based on the electrometallurgical process

(Actinide Recycle System) that can process LWR spent fuel and LMR spent fuel in a low cost, diversion resistant system. Recent studies show that LWR spent fuel can be processed at no cost versus the many hundreds of dollars per Kg required to reprocess in an aqueous reprocessing plant. The ALMR/Actinide Recycle System is configured with a burner core which utilizes the plutonium and minor actinides removed from the LWR spent fuel to produce electricity. Deployment of this system early in the next century provides economical closure of the backend of the LWR fuel cycle and supports the continued use of LWRs.

An additional advantage of the Actinide/Recycle System is that the waste is conditioned prior to disposal by converting it to a highly leach resistant form whose radiological toxicity will decay to the level of natural uranium in less than 300 years, a process that would otherwise take 10,000 years to accomplish.

It is time for the U.S. to re-evaluate its ban on reprocessing as the nuclear genie is already out of the bottle and proliferation risks must be addressed on an international basis. Other nations that are less fortunate with respect to their fossil reserves and are more dependent on nuclear power will proceed with reprocessing whether or not the U.S. continues its self imposed ban. An in-depth assessment of these complex issues is needed now so that the U.S. can complete the necessary research and development work on a schedule that will allow its introduction when needed for low cost energy and low cost waste disposal. It is anticipated that the assessment will confirm that the ALMR/Actinide Recycle System will significantly reduce the demand on the uranium supply and stabilize the price of uranium for future LWRs and that the system will save the U.S. taxpayers billions of dollars in ultimate disposal costs by reducing the size and complexity of the Yucca Mountain repository. The development programs for the ALMR and for the Actinide Recycle System should be continued so that commercialization of the integrated ALMR/Actinide Recycle System can begin as close to the original 2010 date as possible. This will allow the U.S. to take advantage of: (1) the vast energy potential contained in the fissile material contained in present and future stockpiles of spent LWR fuel, and (2) the benefits associated with conditioning the waste prior to placing it in an ultimate repository.

## Discussion

Recycling provides for the separation of the materials in the spent fuel assemblies to recover the highly valuable plutonium and uranium which are then used to produce electricity and thus conserve natural resources. The remaining waste can be placed into a form that is more suitable for permanent disposal and which requires a smaller repository volume. This waste management system is consistent with the current societal approach of separating and conditioning other commercial wastes to conserve natural resources and reduce the impact on the environment. While recycling could be used solely to condition the waste, it would not be economical without using the fissile material to create revenue by producing electricity in a nuclear power plant.

Two different systems are available for recycling spent fuel; the aqueous reprocessing system and the electrometallurgical system. The aqueous system was developed by the U.S. Government in the 1950's as the Purex process and was used in several U.S. Government and privately owned plants for reprocessing commercial light water reactor (LWR) fuel prior to the U.S. Government's initial decision in the late 70's to ban fuel reprocessing. This system is currently used to reprocess spent fuel from light water reactors (LWRs) in France, the U.K., Belgium, and Japan. Development of the electrometallurgical processing system (pyro-processing system) was initiated by ANL (funded by the U.S. Government) in the 1970's for recycling spent fuel for liquid metal reactors (LMRs) in the Integral Fast Reactor (IFR) program.

ANL has made excellent progress in developing this system for the recycling of metal fuel for LMRs and has recently modified the system to be capable of recycling the spent fuel from LWRs. This system is known as the Actinide Recycle System. An industry team (GE and Burns and Roe) worked with ANL for the past five years to develop a conceptual design and cost estimate for a future commercial Spent Fuel Recycle Facility (SFRF), which uses the Actinide Recycle System. The SFRF can process the LWR spent fuel and the LMR spent fuel, fabricate new fuel assemblies for use in an Advanced Liquid Metal Reactor (ALMR), and separate the remaining waste into high level and low level waste. The high level waste will be conditioned in the SFRF to produce a low volume, leach resistance product which will minimize the repository cost and reduce the risk of releases of radioactivity to the environment.[2]

The ALMR/Actinide Recycle System is based on the use of an ALMR which has been under development by the industry team for the past ten years. The ALMR is a unique liquid metal reactor design which utilizes passive shutdown, shutdown heat removal, and seismic isolation to simplify the ALMR, improve its safety characteristics, and make it competitive with ALWR plants. The ALMR plant design incorporates the experience gained in the design, construction, and operation of liquid metal reactors in the U.S. and overseas for the past 40 years.

The ALMR design uses a small, factory fabricated modular reactor system which, when coupled with the passive safety features, results in lower capital and operating costs than any other liquid metal reactor in the world. The current design of the ALMR uses a burner core which consumes the plutonium and minor actinides recovered from spent LWR spent fuel. In 1994, the NRC issued a satisfactory Safety Evaluation Report for the plant. The SFRF combines fuel processing, waste conditioning, and fuel fabrication into a small facility which is collocated on the same site as the ALMR power plant. The capital and operating cost of the SFRF is low due to the use of the small, factory fabricated process equipment used in the electrometallurgical process (Actinide Recycle System) and the efficient sharing of systems and equipment.[2]

The ALMR/Actinide Recycle System is economically competitive with the use of ALWRs and their associated fuel cycles. The use of the ALMR in conjunction with the Actinide Recycle System provides for the recycling of the Advanced Light Water Reactor (ALWR) spent fuel at no cost to the ALWR plant owner, while also reducing the cost of the repository required for long term storage of the residual high level waste. The ability to recycle ALWR spent fuel at no cost to the ALWR plant owner (or to the Government) represents a major breakthrough in the economics of spent fuel disposition. Previous studies[3] identified a cost of $1000/Kg of heavy metal to process the LWR spent fuel to separate the plutonium from the fission products in an aqueous reprocessing plant. This resulted in the conclusion that it would cost $86B to process the 86,000 metric tons of spent fuel that will be available from the current generation of LWRs by the year 2020. This made reprocessing of LWR spent fuel appear to be far more expensive than the $32 B estimated cost for the repository.[3]

The ALWR spent fuel can be reprocessed at no cost to the ALWR plant owner or the Government because this cost is covered as part of the 12.4 mills/kW-hr fuel cycle costs for the ALMR power plant that uses the plutonium and minor actinides extracted from the LWR spent as fuel for the ALMR power plant. This generates revenue which covers the cost of the ALMR power plant and the fuel cycle located within the adjacent SFRF.

Recent studies have shown that a symbiosis exists between the ALWR power plant and its current once-through fuel cycle and the ALMR and its associated electrometallurgical actinide recycle/waste conditioning system located in a Spent Fuel Recycle Facility (SFRF). This is shown in Figure 1 as the enhanced fuel cycle.

This symbiosis reduces the cost of the ALWR fuel cycle by providing recycled uranium and by reducing the 1 mill/kW-hr waste fee by eliminating the plutonium and minor actinides from the high level waste to be placed in the repository (reduction in repository cost). The combination of a cost effective Spent Fuel Recycle Facility and a cost effective ALMR power plant results in the ability to produce electricity from this system for busbar costs that are competitive with the ALWR busbar costs (about 40 mills/kW-hr). This cost competitiveness makes it economically feasible to deploy the ALWR/ALMR system so that the plutonium and minor actinides in the ALWR spent fuel can be recycled, thereby substantially reducing the cost of a repository. In addition, deployment of the ALWR/ALMR system provides for considerably greater diversion and proliferation resistance compared to a once-through ALWR fuel cycle, and potential environmental impacts are significantly reduced.

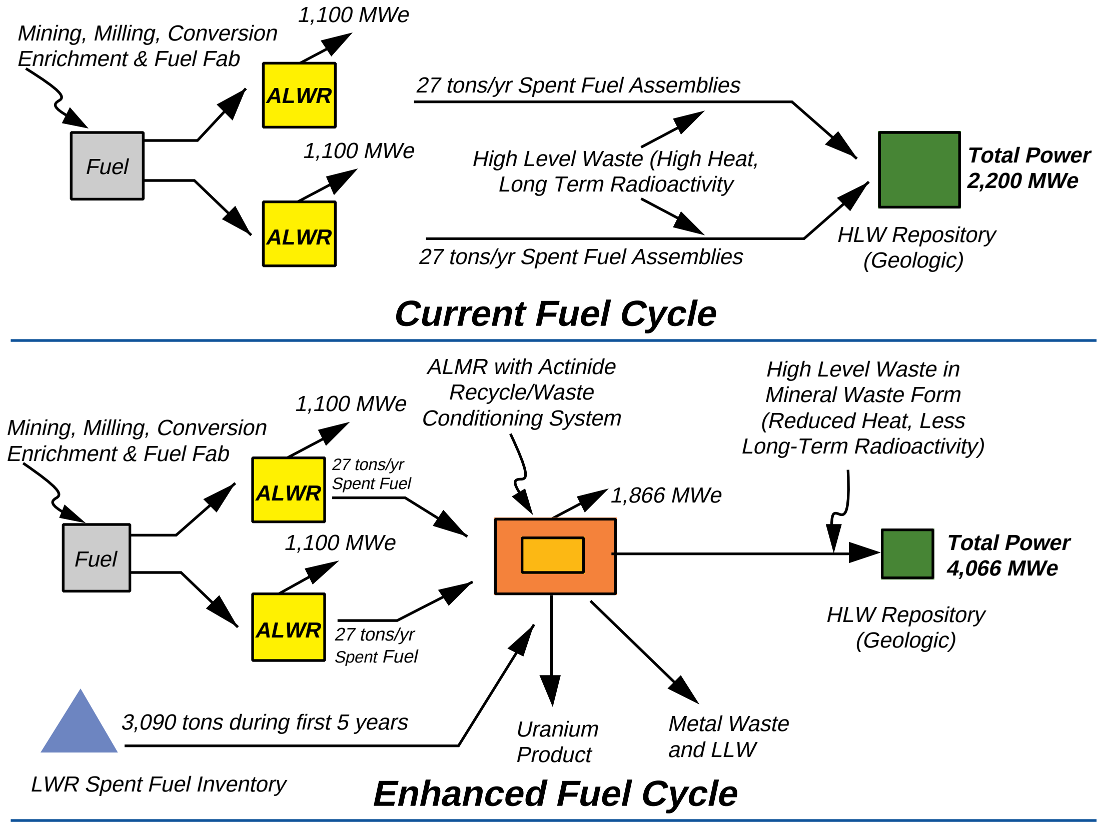


**Figure 1. ALWR/ALMR Fuel Cycle.**

The currently designed 1,866 MWe ALMR power plant with a burner core annually consumes the plutonium and minor actinides contained in 55 MT of LWR spent fuel. This quantity of LWR spent fuel is discharged annually from two 1,100 MWe ALWR power plants. A comparison of the annual material flow in the fuel cycles for two 1,100 MWe LWRs with a once-through fuel cycle versus two 1,100 MWe LWRs with an 1,866 MWe ALMR and an actinide recycle system in a collocated SFRF is shown in Figure 2.

Table 1 compares the quantities of spent fuel, natural uranium, and enrichment services required by the two systems shown in Figure 1. The fuel cycle is closed by the use of an electrometallurgical process (the Actinide Recycle System) located within the SFRF and collocated on the same site as the ALMR plant. Use of this system reduces the cost of new fuel for the ALWRs by using the recovered uranium to offset some of the cost of mining, milling, and enrichment services associated with new ALWR fuel. The repository cost for disposal of the waste which results from recycling the 55 MT of spent fuel will be lower than direct disposal. Net cost savings relative to the direct disposal of spent fuel in the repository will result from the changes shown in Table 1.

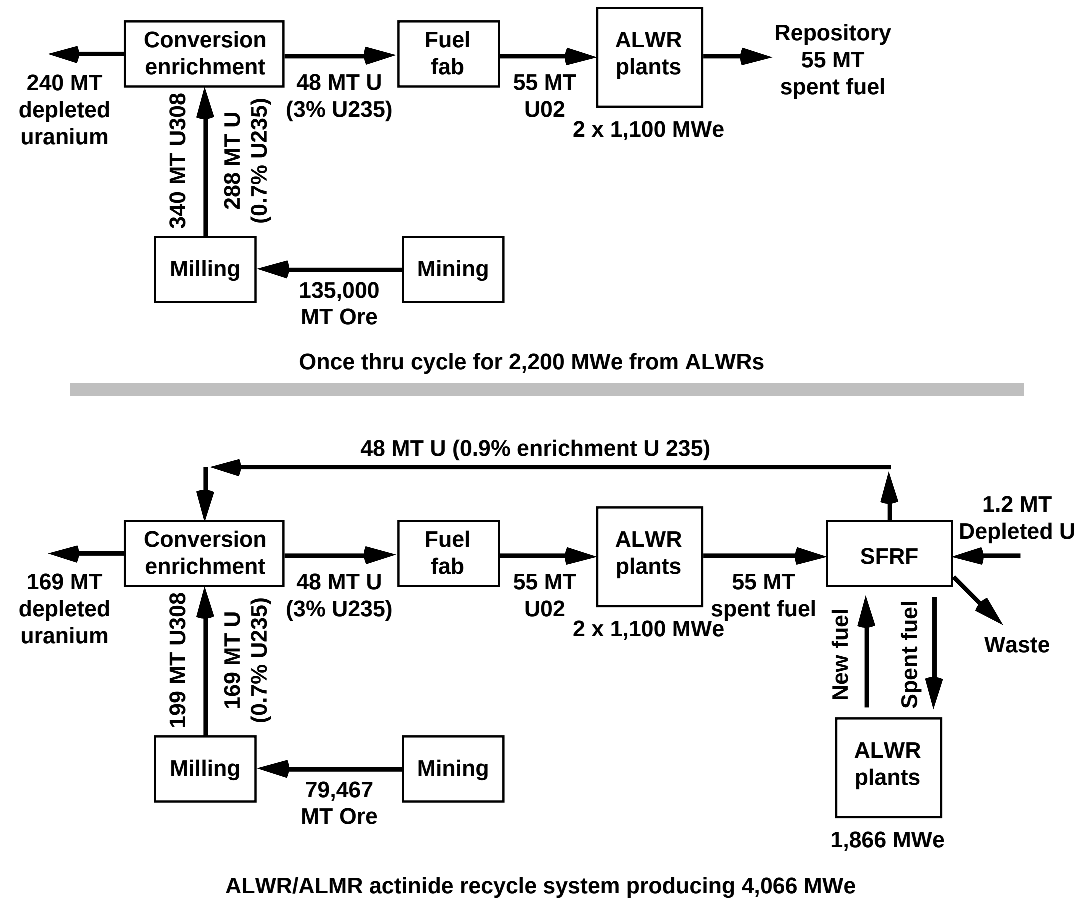


**Figure 2. Annual Fuel Cycle Flow Charts.**

The ability of the ALMR/Actinide Recycle System to recycle the LWR spent fuel at no cost to the LWR plant owner represents a significant economic breakthrough. All costs associated with the SFRF are included in the fuel cycle busbar costs for the ALMR.

The total busbar cost of the electricity produced by the ALMR is competitive with the cost of electricity produced by an ALWR (including its once-through uranium fuel cycle), so that both the ALMR and ALWR can be deployed in a competitive environment, with all fuel cycle costs fully covered for each system. This is illustrated in Table 2. The use of the ALMR/Actinide Recycle System is compatible with the use of ALWRs which operate on the uranium fuel cycle. The fissile materials can be recycled repeatedly in the ALMR/Actinide Recycle System and thus utilize the fissile material more efficiently (produces more electricity) than once through LWR systems. Recycling the plutonium in an ALMR/Actinide Recycle System permits it to produce far more electricity than it would if it were recycled in an aqueous reprocessing/mixed oxide (MOX) system for reuse in LWRs. The MOX fuel cycle only permits recycling the plutonium two or three times, with

**Table 1. Fuel Cycle Comparison.**

| | Total Power (MWe) | ALWR Spent Fuel to Repository | Natural Uranium Supply | Enrichment Services | ALWR Fuel Fabrication |
|---|---|---|---|---|---|
| 2,200 MWe from Once Through ALWR | 2,200 | 55 MT Spent Fuel to Repository | 288 MTU | 184,000 SWU | 55 MT $UO_2$ |
| 4,066 MWe from Advanced ALWR/ALMR System | 4,066 | 0 Spent Fuel Sent to Recycle System | 169 MTU | 162,000 MT SWU | 55 MT $UO_2$ |
| Change | 1866 MWe | 55 MT | 119 MTU | 23,000 SWU | Zero |
| % +/- | 85% Increase | 100% Decrease* | 41% Decrease | 13% Decrease | 0% NA |

* Repository volume required for recycled waste reduced by a factor of four or more.

**Table 2. Cost Comparisons (Mills/kW-hr).**

| | ALMR (1,866 MWe) | ALWR (1,200 MWe) | ALWR (2×1,200 MWe) |
|---|---|---|---|
| Capital | 20.0 | 24.7 | 22.0 |
| O&M | 7.1 | 7.0 | 6.5 |
| Fuel | 12.4 | 8.1 | 8.1 |
| Decommissioning | 1.0 | 1.0 | 1.0 |
| **Total Busbar Costs** | **40.5** | **40.8** | **37.6** |

spent fuel remaining for permanent disposal. The ALMR/Actinide Recycle System provides for the continued use of the plutonium to produce electricity over many years of plant life.

The ALMR/Actinide Recycle System is more proliferation resistant than the MOX fuel cycle due to the inability of the currently designed commercial Actinide Recycle System to separate plutonium from the other minor actinides and the ability of the ALMR to operate with this mixture of fissile material. This mixture of Pu and minor actinides is not suitable for nuclear weapons. The commercial aqueous mixed oxide (MOX) fuel processing system and the operation of the LWR are based on the separation of the plutonium from the minor actinides resulting in a less proliferation resistant system.

Diversion resistance is enhanced by the unique design of the pyroprocess which uses small simple systems and components which are contained in inerted, shielded cells. These features, together with the batch operation, provides for good accountability and physical protection which reduces diversion risks. The location of fuel recycling and fuel fabrication in a common facility and the collocation of this facility on the same site as the ALMR power plants also reduces diversion risks.

Based on the above discussion, reprocessing ALWR spent fuel in an electrometallurgical recycle system that also recycles ALMR spent fuel and is collocated at the same site as the ALMR power plant is a system can provide for a cost effective nuclear power system for the U.S., with a minimum quantity of high-level waste (with essentially no fissile material) to be placed in a repository. This system also increases the diversion resistance of fissile materials and increases the nation’s energy reserves for the future.

## Summary

The ALMR/Actinide Recycle System offers multiple advantages and cost benefits to the U.S. nuclear program as described below.

The U.S. Government can avoid spending a large percentage of the projected $30B cost from the Yucca Mountain repository program by conditioning the LWR spent fuel to reduce the long term heat load and permit a four to one reduction of repository storage volume. Removing plutonium and the minor actinides prior to disposal eliminates most of the long lived radioactive material so that concerns about release of this material to the environment over a 10,000 year period can be reduced to a more manageable few hundred year period. Thus, conditioning the waste prior to disposal will save the U.S. Government and the taxpayers billions of dollars by simplifying the analysis required for the environmental impact statement and licensing, and by reducing the effective size of the repository. Use of the plutonium and minor actinides as fuel to produce electricity in the ALMR provides revenue which fully covers the cost of conditioning the LWR spent fuel at no cost to the LWR plant owners.

Preliminary evaluations indicate that up to a 50 to 1 reduction in repository volume is technically feasible by also removing the two elements with the highest heat load (cesium and strontium) from the waste stream prior to disposal. Further development work is required to confirm that this additional processing step is economically justified, but further reduction in repository cost may be possible.

The use of the plutonium and minor actinides that can be extracted from the LWR spent fuel and used to produce electricity with an ALMR significantly reduces the demand on the uranium supply thereby helping to stabilize the price of uranium at the current low levels. Utilizing the uranium recovered from the spent LWR fuel to make new LWR fuel reduces its near term fuel cost while also reducing the demand for uranium and stabilizing the price.

Spent LWR fuel from the current generation of LWRs can be removed from the interim storage facility or from utility fuel pools at a rate commensurate with the deployment rate of the ALMR/Actinide Recycle System. The total 86,000 metric tons (MT) of this inventory that will be accumulated by 2020 can be used for the startup of about 40 ALMR plants. A deployment rate of one ALMR/Actinide Recycle System per year permits depletion of this inventory in 40 years. By the use of burner cores, the continued operation of the ALMRs can utilize the spent fuel from future ALWRs to avoid a buildup of inventory of LWR spent fuel in the future. This provides for prompt utilization of the plutonium contained in the ALWR spent fuel and improves the fuel cycle economics while reducing the proliferation potential.

The ALMR/Actinide Recycle System keeps the plutonium and minor actinides that are removed from the LWR spent fuel fully contained within a closed loop consisting of a reactor and a fuel recycle facility located on the same site. This provides a system which is highly resistant to diversion and proliferation and can meet all IAEA and NRC safeguards, security, and accountability requirements.

Early deployment of the ALMR/Actinide Recycle System provides for stability of the fuel cycle costs (front end and back end costs) throughout the 40 year operating lifetime of the future ALWRs. This stability is an important aspect in the future use of nuclear power in the U.S.

## Conclusion

Progress on the development of the ALMR/Actinide Recycle System has been excellent, with no major problems identified. However, funding for development of the ALMR power plant and the Actinide Recycle System was eliminated by Congress in 1994 in response to an initiative by the Executive Branch.

The five billion dollar cost to complete the development of the ALMR/Actinide Recycle System can be funded through Government/industry cost sharing since all parties can derive future cost benefits that far exceed the development costs.

The ALMR/Actinide Recycle System also has the potential to provide an almost limitless supply of energy in the future. This is achievable by reconfiguring the ALMR core to breed more plutonium than it consumes by using the vast stockpiles of depleted uranium as an energy source. This may be considered later in the 21st century if uranium supplies for ALWRs become too expensive and if other more economical energy sources fail to materialize.

## Related Activities

Following the Global 95 Meeting in Versailles, France in September, 1995, two other papers were presented on this topic:

"Cost Effective Fuel Cycle Closure," by C. Ehrman (Burns and Roe) and C. Boardman (General Electric) presented at the American Nuclear Society, Winter Annual Meeting in San Francisco on November 1, 1995 (Vu-Graphs also provided).

"Integrating ALWR and ALMR Fuel Cycles," by C. Boardman (General Electric), M. Thompson (Consultant), C. Ehrman, C. Hess, M. Ocker (Burns and Roe) presented at the ASME/JSME ICON-4 Meeting in New Orleans on March 11, 1996 (Vu-Graphs also provided).

From October, 1995 to March, 1996, a draft of the National Academy of Science STATS Committee report on Separation and Transmutation of LWR spent fuel was reviewed by the authors of the papers noted above, plus C. Walter of Lawrence Livermore National Lab, and H. Bengledorf, B. Wolfe, K. Davis and others. Comments were submitted to the STATS Committee requesting revision to the report to include the information about the use of the ALMR Actinide Recycle System to process the LWR spent fuel in a cost effective manner as discussed in this report. Unfortunately, the final STATS report issued in March, 1996 does not provide the current perspectives on the ALMR Actinide Recycle System. Further efforts will be made to inform others of the advantages of the use of the ALMR Actinide Recycle System to utilize the plutonium in the LWR spent fuel and avoid disposal of it in a repository.

It is noted that since the March 1995 completion date of the DOE contract with the GE Design Team for work performed on the ALMR Actinide Recycle System, none of the work involved in preparing and presenting papers was done under DOE contract. The work was performed largely at the expense of each individual noted above.

## References


1. Quinn, J.E., "Realizing the World Economic, Environmental, and Non-Proliferation Benefits of the ALMR Actinide Recycle," The International Symposium on Global Environmental and Nuclear Energy Systems, Shizuoka, Japan, October 24-27, 1994.
2. Ehrman, C.S., Hess, C.W., Ocker, M.T. (Burns and Roe Co.), "Design Considerations for a Pyroprocess Recycle Facility," Presented at Global 95 Meeting, Versailles, France, September 1995.
3. Ramspott, L.D., Choi, J., Halsey, W., Ponsternak, A., Cotton, T., Burns, J., McCabe, A., Colglazier, W., and Lee, W.W.L, *Impacts on New Developments in Partitioning and Transmuting on the Disposal of High-Level Nuclear Waste in Mined Geologic Repository*, UCRL-ID 109203, Livermore, CA, Lawrence Livermore National Lab, 1992.
4. Ehrman, C.S., Hess, C.W., Ocker, M.T. (Burns and Roe Co.), "Fuel Cycle Facilities Design Report and Cost Estimates," GEFR-00942, Prepared by Burns and Roe Company for DOE as part of the GE Team on the ALMR/Actinide Recycle Program (Applied Technology), March 1995.